DEVELOPMENT AND APPLICATION OF INTEGRATED GEOMETRY CONTROL SYSTEM IN INCHEON CABLE STAYED BRIDGE

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Abstract

The integrated geometry control system in the long-span steel deck cable-stayed bridge has been developed and applied to Incheon Cable Stayed Bridge. This system consists of 4 systems which are data integrated management system, structural analysis system, error adjustment system and measurement system. Each system is integrated and managed in order to combine the systems organically. Four numbers of cables in the side-span and center-span section of Incheon Bridge have been erected and adjusted at the same time by using this integrated system. The results of the final geometry and tension error after closing shows that all the relevant values are fully satisfied within the target ranges.

1. Introduction

Incheon Bridge Project CSB(Cable Stayed Bridge) section with 800m long main span is the longest one in Korea and the 5th longest one in the world among the world's Cable-Stayed Bridges in service or under construction. The superstructure is designed as Steel Plate Box Girder and consists of 5 spans continuous girder systems (span formation : 80+260+800+260+80=1480m). The pylon is designed as inverted 'Y' shape with 225.5m height, consisting of hollow rectangular concrete columns and pre-cast concrete cross beam.
Incheon Bridge CSB section tends to be highly sensitive to the displacement against the load since it has flexible girder stiffness and long span length. And also, the cable nonlinearity seems to be high as the cable length is approx. max. 420m and the sag ratio is about 1/100. The 4 numbers of cables in the side-span and center-span have been erected and adjusted at the same time to meet the work progress schedule. The cycle time for each cable erection is limited at 6~7 days and minimization of cable retensioning after closing of center span are also required.
Therefore, the effective geometry control system is required, which allows the engineer to manage and analyze the geometry data and tensioning data quickly and to decide the adjustment amount of cable tensioning within the shortest time.

2. Development of Geometry Control System

For the geometry control of the long-span length cable-stayed bridges such as Incheon Bridge CSB section, the necessary data shall be measured and be put into the analysis program to compare with the target value and calculate the error in order to estimate the adjustment of the cable-length. And also, these said processes shall be done during a very short period, therefore the geometry control system is developed.
Incheon Bridge project geometry control system, SGCS(Samsung Geometry Control System), consists of the integrated data management system, structural analysis system, error adjustment system and survey/management system. These 4 kinds of systems are organically integrated for the geometry control.

2.1 Integrated Data Management System

In order for the geometry control of the CSB section, a large number of data such as analysis data, survey data and structure's temperature data shall be analyzed during the short time

period and at the final stage, the tensioning adjustment shall be calculated. Therefore, the integrated data management system(SGCS) is developed.

In the integrated data management program, there are functions to store the geometry control data, to classify the stored data and show them through the graphic, and to perform the comparative analysis for analyzed values and measured values. These functions offer the user to select the necessary data and compare/analyze them. Therefore, it allows to easily understand about the cause and development of the error. Followings (Fig.1) are shown the integrated data management program

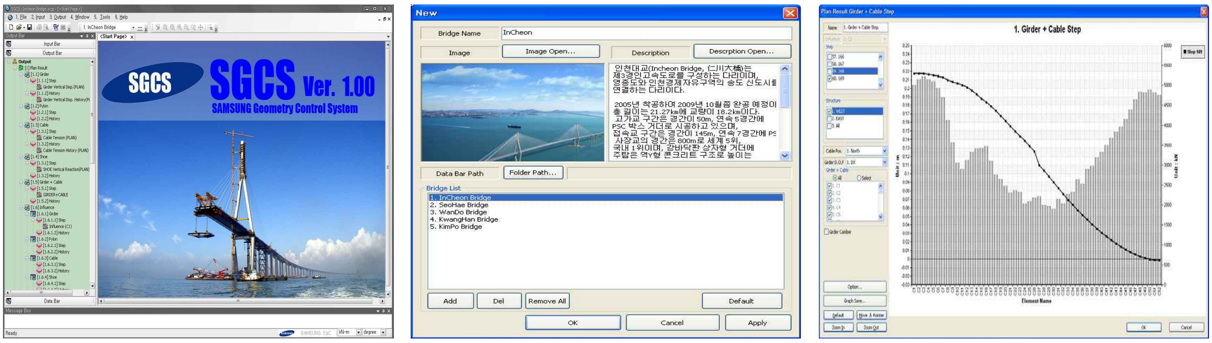

Fig. 1. Integrated Data Management Program

2.2 Structural Analysis System

The cable bridge is the structure with a high geometric nonlinearity, therefore, the analysis program possible to implement the cable's non-linearity, the stiffness increase by the axial load of the structure, and the geometry non-linearity shall be used to obtain the correct structural analysis result in the geometry control.

BANAM(Bridge Analysis by Numerical Analysis Method) is applied as the Incheon Bridge CSB section analysis program, which was developed by Samsung corporation. In this method, the solution can be obtained by using the elastic catenary element, and also the geometry nonlinearity is considered so that the correct solution can be estimated in analyzing the long-span cable-stayed bridge like the Incheon Bridge project. And, Post-processing program is

developed and applied to the geometry control in order for the prompt application and analysis of the analysis results.

The initial equilibrium state analysis(TCUD) for the determination of the initial geometry , and the stage by stage analysis during construction have been carried out before the cable installation progress. The influence matrice for displacements and tensioning forces by cable unit tensioning have been made for the error adjustment, and the sensitivity analysis due to temperature variation and gradient have been also carried out.

2.3 Error Adjustment System

In the construction of cable-stayed bridge, the cable tension and geometry of the girder/pylon are very important issues for the construction work management. The geometry of the CBS section, in particular to the deflection of the girder is required to attain the correct longitudinal design level. The cable tension is required since it acts as the load to the structure and affects the size of the member force, and moreover it makes the cable to have proper stiffness as a structural member. However, the actual load and actual sectional properties in girder, pylon and cable work is different from the design load and design sectional properties, and due to many other error causes, there is a difference of designed geometry and tension. Therefore, in each work stage, the adjustment of the geometry /tension is necessary to make the actual cable geometry and cable tension to meet the design values based on the measured values. The adjustment of the cable length to minimize the error in geometry and tension can be calculated with the following equation (1) of the optimization problem.

$$\underset{\Delta\mathbf{L}_0}{\mathrm{Min}}\,\Pi = \frac{1}{2}\sum_{i=1}^{nm}\left(\frac{u_i^c - u_i^A(\mathbf{L}_0+\Delta\mathbf{L}_0)}{\alpha_i\cdot(u_{i\max}-u_{i\min})}\right)^2 + \frac{1}{2}\sum_{j=1}^{nc}\left(\frac{T_j^c - T_j^A(\mathbf{L}_0+\Delta\mathbf{L}_0)}{\beta_j\cdot(T_{j\max}-T_{j\min})}\right)^2$$

$$\begin{aligned} &\text{subject to } u_{i\,\min} \le u_i \le u_{i\,\max} \qquad (1)\\ &\text{subject to } T_{\min} \le T^A(\mathbf{L}_0+\Delta\mathbf{L}_0) \le T_{\max}\\ &\text{subject to } \Delta\mathbf{L}_{0\min} \le \Delta\mathbf{L}_0 \le \Delta\mathbf{L}_{0\max}\end{aligned}$$

In the above equation, u_i^c is target geometry and u_i^A is actual structure displacement. And, $u_{i\,\max}$ and $u_{i\,\min}$ are the max. and min. limit of structure displacement error respectively. T_j^c and T_j^A means target tension and actual structure cable tension. $T_{\max}$ and $T_{\min}$ are the max. limit of cable tension. $\mathbf{L}_0$ is cable's unstressed length, and $\Delta\mathbf{L}_0$ is adjustment of cable length. nm and nc mean the number of displacement checking points and the number of cable to be measured. The above equation (1) is the optimization problem with non-liner constraint

condition, and the weighting factors of α_i and β_j are adjusted to estimate the optimum $\Delta\mathbf{L}_0$. The weighting factor is the item only used in case that the engineer decides the necessity of the local error adjustment in consideration of the accuracy in survey/measurement, the error adjustment pattern for the already-erected segment and the relation between the already-erected segment and the to-be-erected segment even if the error is within the allowable range

2.4 Measurement System during Construction

Incheon Bridge CSB section measurement system is prepared as shown in Fig.2 below in order to collect the accurate and prompt measurement data for the geometry control. Thermometers are installed at girders, pylons, temporary bents, and cables and the temperature data is used in the analysis in work stages for the error adjustment. Angle meter, GPS, electronic wave surveying prism are installed to check the displacement of the pylon. As the erection work proceeds, the survey is carried out with 45m interval in order to check the girder's vertical displacement history and the overall deflection geometry .
Cable tension (Fig.3) is measured by combination of two methods to minimize the measurement error, such as vibration method with accelerometer and tension measurement method by Hydraulic jack. And, wireless communication system is used to collect all measurement data (temperature of structure, displacement of pylon, etc.) immediately. (Fig.4)

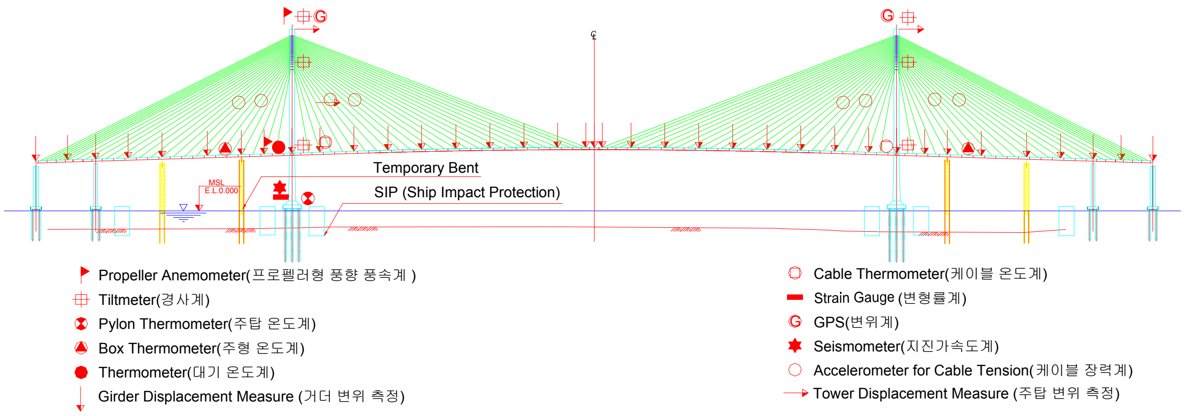

Fig. 2. Measurement System

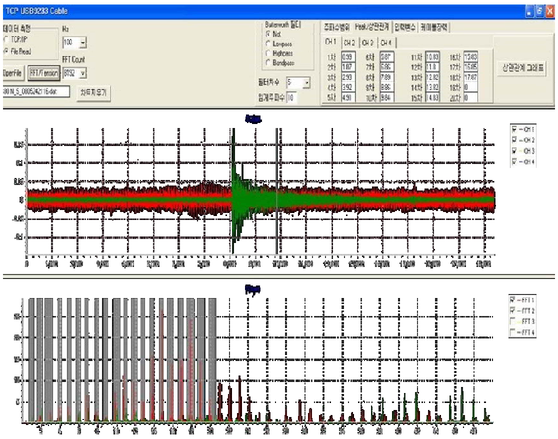

Fig. 3. Tension Measurement Programme

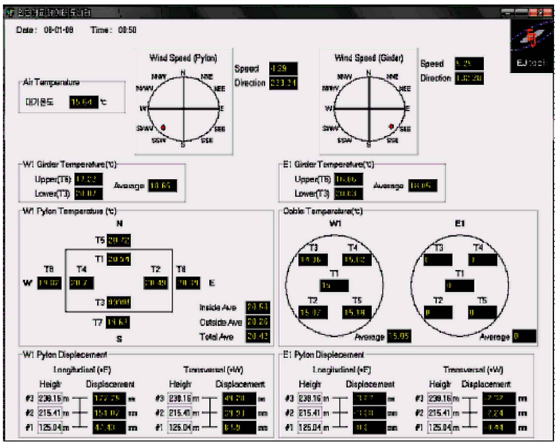

Fig. 4. Monitoring Programme

3. Application of Geometry Control System

3.1 Construction Method of Incheon Bridge CSB Section

The side span segments have been erected as 4 nos. of large blocks supported by the temporary bents. The center span segments are erected by Cantilever method together with cables. Following Fig.5 shows the erection of the Incheon Bridge CBS section.

The cantilever erection procedure of the CSB superstructure is i) girder erection, ii) side-span equipment movement, iii) center-span equipment movement, iv) side-span cable installation, v) center-span cable installation and vi) derrick crane movement. Among the said erection procedure, the girder erection and the cable installation at the side span & center span including the final tensioning stage are very important in the geometry control.

In the girder erection stage, the weld shrinkage on the girder joint is managed and the girder joint angle is adjusted in order to minimize the girder erection error. And, in the cable tensioning stage, the error is checked thru the survey and measurement after inserting the cable design shim and the final adjustment ship is calculated by the error adjustment at night.

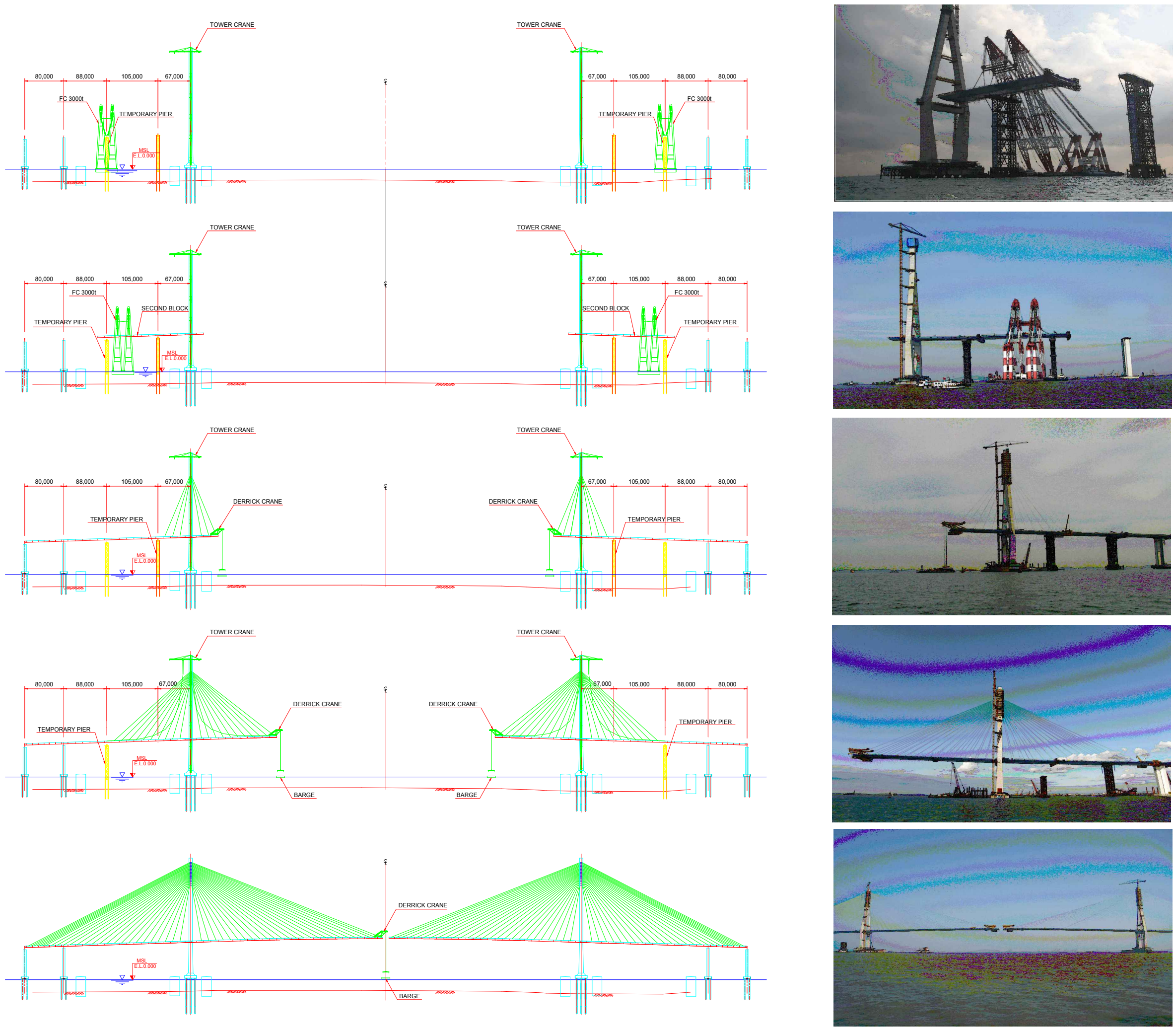

Fig. 5. Erection Procedure

3.2 Geometry Control in Work Stages

Incheon Bridge construction is divided into total of 169 stages. Only 60 work stages are considered in the geometry control. It includes the small-segment joint work stage and the cable tensioning stage, as well as the temporary bent removal, the side-span count-weight load stage and the paving load stage.

In order to meet the design joint angle in the small-segment erection, the relative deflection between the already-erected segment and the to-be-erected segment is measured during the day. Especially, the geometry control for the cable tensioning during the night (no temperature change) is carried out at 4ea cables (side-span & center-span) at the same time with the cable tensioning. This is first to carry out in the geometry control with the cable tensioning, therefore, the cable installation cycle could be reduced. Following Fig.6 shows the

geometry control plan for small-segment joint angle management and cable tensioning. The geometry control steps for each work are as shown in Table 1 below.

Fig. 6. Geometry Control Plan : Small-Segment Joint & Cable Tensioning

STEP	Small-Segment Erection	Cable Installation
1	Analysis	1st Survey/Measurement
2	Survey	Analysis
3	Joint Angle Adjustment	Error Adjustment (Shim Adjustment)
4	-	2nd Survey/Measurement
5	-	Point Survey
Remarks	Day Survey	Night Survey

Table 1. Geometry Control Step

3.3 Geometry Control Result

The result of the geometry control is presented in Fig. 7 & 8, applying the geometry control system developed in this study. In comparison of the analysis value and measurement value for the girder vertical level, there was error occurred at the center section -78mm(C53) and max. +85mm(C44). This is fully satisfied with the geometry control target range ±200mm and the level error management target value presumed by 2nd parabola. And also, the error of pylon inclination is -56mm(West) and +51mm(East), so they are within the target range

±110mm.

In case of the cable tension, the excess of the target value (10% of the introduced tension) are occurred at 3 numbers of cables. Considering the affect of adjacent cable due to adjustment of cables, total 4ea of cables are finally adjusted. The amount of cables shim adjustments including the final 4 numbers of cable adjustments are shown in Fig.9.

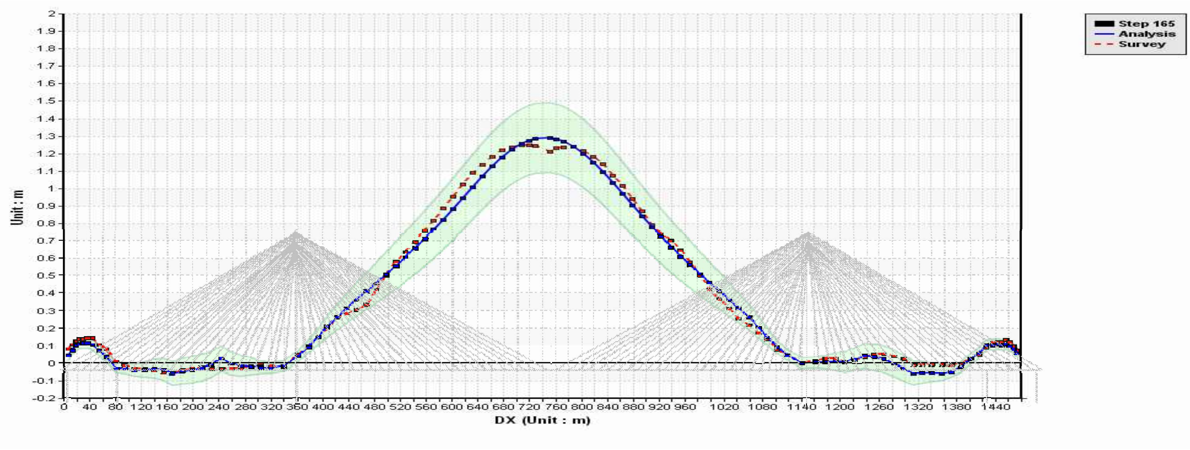

Fig. 7. Final Girder Geometry after Closing (Web in Northern Section)

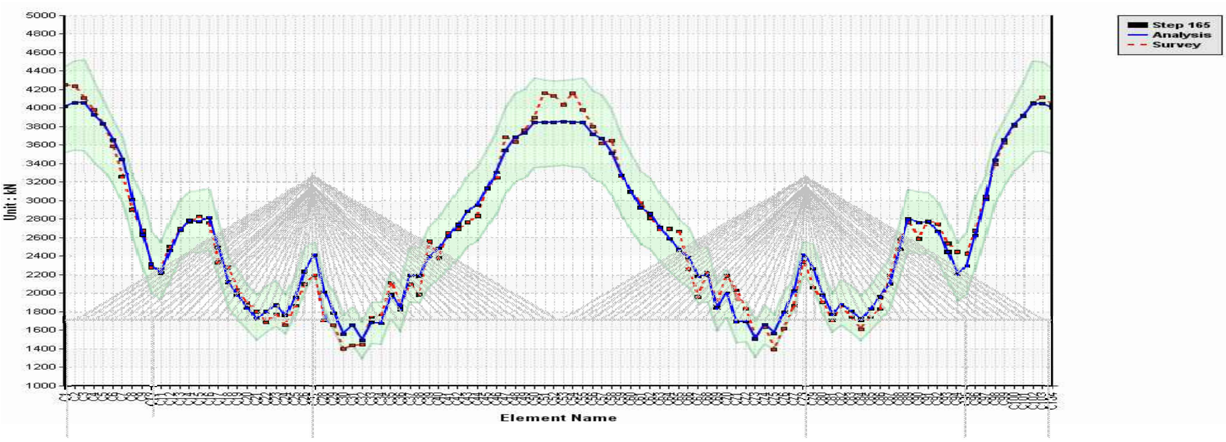

Fig. 8. Final Cable Tension Distribution after Closing (Cable in Northern Section)

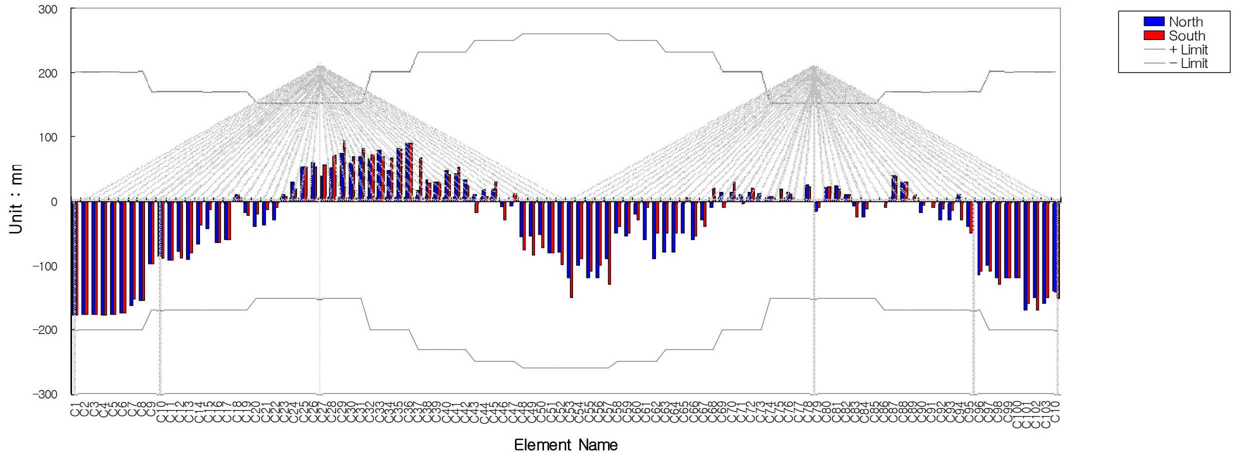

Fig. 9. Cable Shim Adjustment

4. Conclusion

This study is to develop the geometry control system in the long-span steel deck cable-stayed bridge. It is applied to the geometry control of the Incheon Bridge CSB section to verify its applicability. The conclusions are as following.

1. The geometry control system for the Incheon Bridge CSB section consists of the data management system, structural analysis system, error adjustment system and measurement system. These systems are integrated and managed in order to combine the systems organically.
2. In order to reduce the construction period of the steel deck cable-stayed bridge, the geometry control work shall be performed at the same time with the cable tensioning at 4ea of cables in the side-span and center-span section. And, in order for the efficient application of the geometry control system, the data wireless communication system and the data analysis programme are required to understand the geometry and figures of the structure quickly.
3. The geometry control of the Incheon Bridge CSB section is performed by using the developed geometry control system. And, it is revealed that the final geometry and tension error after closing is fully satisfied with the target range.

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